# Aluminium as a construction material in ammonia refrigeration cycles

## Experiences with Aluminium

Compared to other metals, aluminium has only a brief history as an engineering material. It was first produced as a metal some 150 to 190 years ago. The first heat exchangers with aluminium pipes were used in ammonia cycles about 60 years ago. Other components made of aluminium, which have proven reliability for many years, include seals and structural components for compressors (pistons, connecting rods, cylinder heads, crankcases, etc.). These components are made of wrought and cast alloys.

Wrought alloys are semi-finished and finished products with sufficient elongation at break (mostly greater than 8%) shaped by rolling, drawing, pressing and forging. Tensions resulting from cold forming can be removed by means of soft annealing (up to 250°C). Cast alloys are suitable for sand and chill casting and, alongside other alloy elements, usually contain up to three per cent of magnesium or silicon.

Due to the specific chemical properties of ammonia, steel has predominantly been used for the essential construction elements, such as pipes, heat exchangers and vessels, in ammonia cycles. This is also a result of the widespread use of ammonia in industrial refrigeration systems. To develop ammonia applications in the commercial refrigeration sector, technologies are needed that are familiar to those used with HFC refrigeration systems (soldering and detachable joints) and which are lower cost. In this respect aluminium offers the best characteristics as a construction material.

**Properties of aluminium (Al)**

(in comparison to those of copper (Cu) predominantly used in HFC cycles)

| | | 99 % **Al** | 99,9% **Cu** |
|---|---|---|---|
| Density | $10^3$ kg/m³ | 2.7 | 8.9 |
| Thermal conductivity | W/(m·K) | 230 | 310 |
| Electrical conductivity approx. | m/(Ω · mm²) | 36 | 58 |
| 0.2 yield strength approx. | N/mm² | 60 | 160 |
| Thermal expansion | $10^6$ 1/K | 23.8 | 16.2 |
| Melting point | °C | 660 | 1083 |

**Advantageous properties of aluminium are:**

- Cost-efficient and malleable (ductile)
- Good machinability
- Toughness at sub-zero and, therefore, suitable for evaporation temperatures below −10°C
- Suitable for soldering and welding
- Hygienic
- Reusable
- Cheaper than copper – although this varies over time

**Aluminium alloys**

Not all aluminium is the same. In molten state it can be alloyed with copper, magnesium, manganese, silicon, iron, titanium, beryllium, lithium, chromium, zinc, zirconium and molybdenum in order to foster certain properties or to prevent other undesired characteristics.

According to standard EN 573-3/4, the following forgeable aluminium alloys can be distinguished:

- Group 1xxx with aluminium content of at least 99% and with a strength of 70 to 190 N/mm²
- Group 2xxx with copper content of 0.7 to 6.8% and strength of 190 to 570 N/mm²
- Group 3xxx with manganese content and strength of 100 to 350 N/mm² (is often used as material for core tubes of heat exchangers)
- Group 4xxx with silicon content of 0.6 to 21.5% and strength of 170 to 380 N/mm²
- Group 5xxx with magnesium content of 0.2 to 6.2% and strength of 100 to 450 N/mm²
- Group 6xxx with magnesium and silicon content of about 1% and strength of 100 to 450 N/mm²

- Group 7xxx with zinc content of 0.8 to 12.0% and strength of 220 to 700 $N/mm^2$
- Group 8xxx containing other elements ( aluminium lithium alloys)

**Regulations for the use of aluminium**

According to EN 378, aluminium and aluminium alloys can be used in any component of the refrigeration cycle if their strength is sufficiently high and they are compatible with ammonia and the employed lubricants.

**Substances in contact with Al components**

In the refrigerant cycle of an ammonia system, aluminium constructed components come into contact with ammonia, refrigeration oil, traces of water and other metals. Refrigeration oils used in ammonia systems are either mineral and synthetic oils insoluble in ammonia or polyalkylene glycol (PAG) synthetic oils, which are soluble in ammonia and have been available since approx. 1993. The different hygroscopicity of these oils leads to different corrosion conditions.

For secondary refrigerant cycles, the compatibility of water and aqueous solutions of antifreeze agents with the used aluminium alloys needs to be proved in each individual case. Outside of the cycle, the surfaces of Al construction elements are exposed to air and subject to corrosion if the temperature drops below the dew point and condensate forms. In case of $NH_3$ leakages, the condensate absorbs the ammonia for form a weak solution.

**Corrosion behaviour**

Aluminium is not corrosion-resistant in itself and, therefore, aluminium components are at risk of corrosion. As a result of the corrosive attack, a thin, dense oxide layer forms on the material surface, making the originally base aluminium relatively corrosion-resistant against attacks by air and humidity. This technique is known as passivation. However, the properties can change significantly through the influence of different alloys. For ammonia cycles, aluminium alloys with the following corrosion resistances are available:

**Construction elements in the refrigerant cycle**

- No measurable corrosion in pure, dry $NH_3$
- Negligible corrosion from a technical viewpoint (only a few µm/a) in the case of contact with $NH_3$ and refrigeration oil showing different corrosion rates depending on the type of oil, aging of the oil, and the water content.

- If insoluble mineral and synthetic oils are used, due to their limited absorptiveness of water (100 to 200 ppm), no corrosion problems are expected.
- If soluble PAG oils are used, the absorptiveness of water increases. This may induce changes in the oil and can lead to chemical reactions with aluminium components in the compressor, resulting in a considerably reduced service life.

**Construction elements in the secondary refrigerant cycle**

- The corrosion behaviour of heat exchanger pipes can be disregarded if ethylene glycol water mixtures are used as intermediate substances. For other secondary refrigerants, extensive studies and tables now exist in which the authors propose suitable inhibitors for the different fluids.
- If other metals (e.g. copper) are used in the secondary refrigerant cycle, considerable corrosion can be expected if ammonia can enter the secondary refrigerant cycle. In particular if cycles are not saturated with nitrogen, a complete breakdown is possible, in extreme cases after only 0.5 to two years. Therefore, the combinations of materials have to be analysed.

**Construction elements in contact to the environment**

- Aqueous solutions of ammonia cause technically unacceptable corrosion. This puts especially aluminium components at risk~~,~~ which come into contact with aqueous solutions due to temperatures below the dew point and leakages. For such components, however, manufacturers offer various coatings as corrosion prevention, which ensures the corresponding service life of the components.

**Stress corrosion cracking behaviour**

The aluminium alloys intended for use in ammonia cycles are not affected by stress corrosion cracking.

**Connection technologies**

Permanent joints of pipes produced by hard-soldering of aluminium/aluminium and aluminium/austenitic Cr Ni steels are mechanically solid and corrosion-resistant. In the case of soldered joints of aluminium with non-alloy or low-alloy steels, corrosion has to be expected at the joint. By rolling aluminium pipes into steel panels, shell-and-tube heat exchangers can be manufactured permanently sealed.

For detachable joints there are a number of safe solutions, which remain tight and corrosion-resistant both after multiple disconnections and under alternating pressure load and temperature changes.

### Aluminium in electric motors

Hermetic compressors with copper motor windings used in HFC systems cannot be used in ammonia cycles. Since 1993 semi-hermetic compressors, whose motors have aluminium windings and a special insulation system, have successfully been used in ammonia cycles. Thus, these compressors do not need the wear-sensitive shaft seal required for open compressors. The ammonia cycle is only closed by static sealings. Correspondingly, due to the lower conductivity of aluminium in comparison to copper (approximately 65%), the sizing of these motors needs to be different.

### Conclusion

Aluminium alloys have proved reliable as construction materials in ammonia cycles for years. For the application of technologies familiar to refrigeration technicians from HFC systems, construction elements of aluminium alloys offer safe solutions with regard to corrosion resistance and mechanical strength. Therefore, the advantages of the refrigerant ammonia with regard to considerably smaller dimensioning of pipes, fittings and valves can be combined with the advantages of the construction material aluminium.

In case of doubt, the German-language original should be consulted as the authoritative text.

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